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INVESTIGATION OF BIAXIAL STRESS CORROSION IN TWO ALLOYS

(Final Report)

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FOREWORD

This report was prepared by the Chemical and Material Sciences organization of the Research Division of Rocketdyne, a Division of North American Aviation, Inc., in compliance with Contract NAS9-6324, Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas. The report covers the period from 29 June 1966 to 28 May 1967. The contract monitor was Mr. S. Glorioso.

Dr. A. J. Jacobs was principal investigator. Others who cooperated in the research and the preparation of the report were: Dr. R. P. Frohmberg, Program Manager; Mr. E. D. Weisert, Technical Management; and Dr. W. T. Chandler, Responsible Engineer. Mr. G. Dyer performed the experiments. Messrs. J. N. Lamb and J. Jortner contributed helpful discussions.

ABSTRACT

The experimental program was carried out to determine the effect of a biaxial (1:1) stress state on the stress-corrosion resistance of 7075-T6 aluminum and 347 stainless steel. Tubular specimens of these alloys were loaded in simple tension or were loaded in tension and pressurized to obtain the biaxial stress state. A total of 40 aluminum specimens, 20 short transverse and 20 long transverse, were subjected to alternate-immersion tests in a 3-1/2 percent NaCl solution at room temperature. The short transverse specimens were tested at 65 and 32.5 percent of yield strength, and the long transverse specimens at 80 and 65 percent of yield. Forty-two stainless-steel specimens were continuously immersed in a constant boiling (309 F) aqueous solution of $MgCl_2$. These were investigated at 50 and 65 percent of their yield strength. Balanced biaxial loading compared with uniaxial loading is as follows in its effect on stress-corrosion life. The short transverse 7075-T6 specimens tended to survive somewhat longer under biaxial loading; however, there was no discernible effect in the case of long transverse specimens. A tendency was observed for the lifetime of 347 stainless steel specimens to be shortened under the application of biaxial stress. A number of the stainless-steel tests were invalidated because the epoxy coating on the stressing frames was permeable to the $MgCl_2$ solution.

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INTRODUCTION

Stress corrosion of tankage and capsules can be a catastrophic failure mode in space vehicles. New insights into texture strengthening have shown advantages in having a tank wall, for example, in balanced biaxial tension. An important technical question, then, is whether a state of balanced biaxial tension will adversely affect the stress-corrosion behavior of space vehicle materials.

The term stress corrosion is a generic name for delayed failure caused by the combination of chemical and stress environments in which the material operates. Since vastly different mechanisms can be operative in establishing the environment-sensitive mechanical properties, it was felt that studies on the interaction between a balanced biaxial stress field and stress corrosion should be performed with a minimum of variables. The use of a pressurized cylinder appeared to be the optimum method for duplicating tank and capsule biaxial stresses. It was decided to perform at least one of the experiments on an alloy/environment system for which the mechanism was fairly well understood.

Before pressurized testing is carried out in environments presenting experimental difficulties, such as nitrogen tetroxide or molten salts, the effects of biaxial stresses should be studied in simple, economical alloy/environment systems. Therefore, 7075-T6/salt solution and 347 stainless steel/boiling $MgCl_2$ solution were selected as the alloy/environment systems for study.

To understand the interaction between the various stress-corrosion processes and biaxial stress fields, both data and knowledge of the mechanisms involved are required.

Rocketdyne has been engaged for the past several years in an intensive study of the mechanism of stress-corrosion cracking in the precipitation-hardenable aluminum alloys(Ref. 1 through 5). Although particular emphasis has been placed on the 7075 alloy, results indicate that a general mechanism may hold for this entire class of alloys. The essential ingredients seem to be pinned dislocations and neighboring grain boundary pits. The dislocations arise from the differential thermal contraction of precipitate particles and the aluminum matrix or from other stresses around the particles, while the pits originate from the anodic dissolution of the particles themselves (as in 7075) or of the areas surrounding the particles (as in the 2000-series alloys). Because the dislocations are favored nucleating sites for precipitates, they become immobilized during the aging process, and localized plastic flow becomes difficult. Plastic flow is necessary if dangerous stress concentrations, inherent in the stress-corrosion process, are to be avoided.

Uniform biaxial stresses do not result in zero shear stress for three-dimensional materials. In Fig. 1a, it can be seen that the shear stress would be eliminated in the xy plane because

$$\tau_{max} = \frac{\sigma_x - \sigma_y}{2} = 0.$$ However, $\sigma_z = 0$, so the equations

$$\tau_{max} = \frac{\sigma_x - \sigma_z}{2} = \frac{\sigma_x}{2}$$

and

$$\tau_{max} = \frac{\sigma_y - \sigma_z}{2} = \frac{\sigma_y}{2}$$

still apply. The maximum shear stress is numerically equal to the value it would have in the uniaxial case. The maximum shear stress still operates on planes of the types aehd (or cgfb) and gdbe (or achf), Fig.1b,

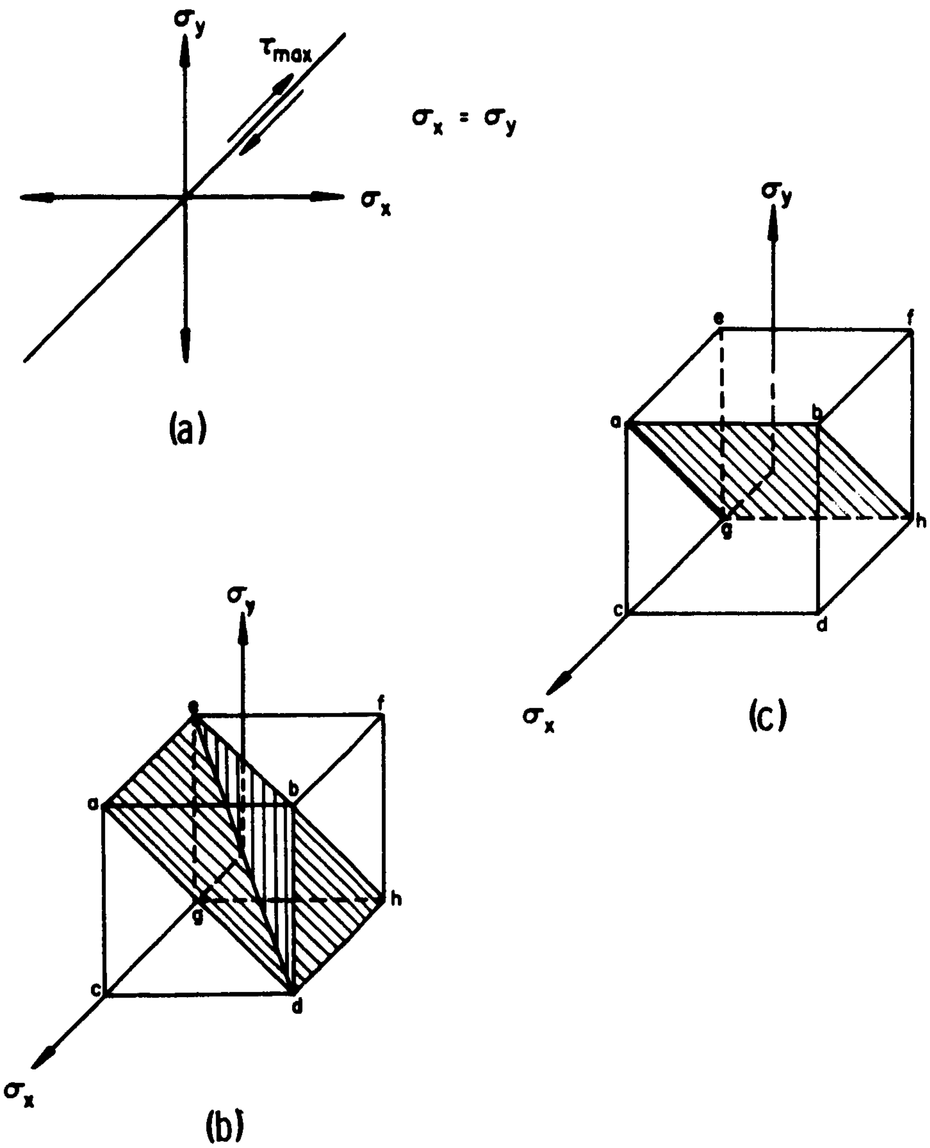


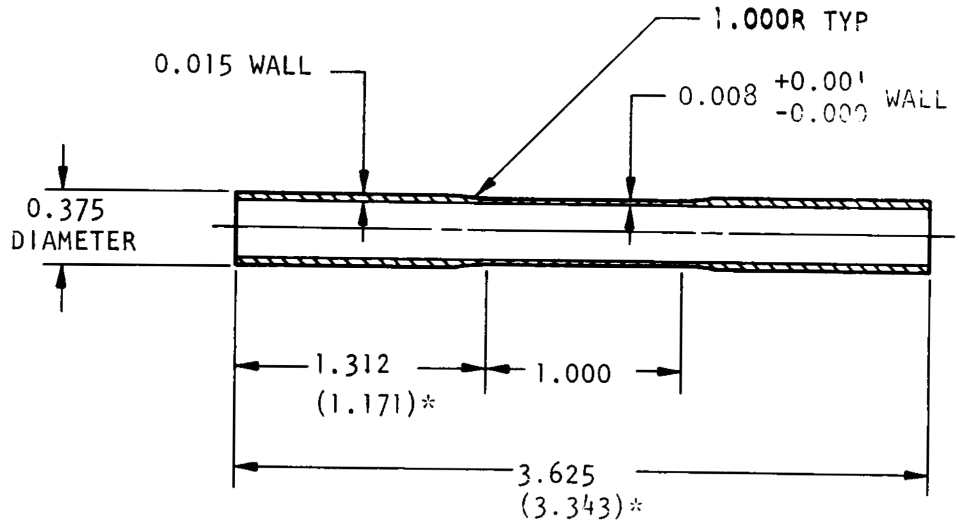
Figure 1. Shear Planes Under Equal Biaxial Stresses

but not on the plane abhg (or cdfe), Fig. 1c. Thus, the number of operative shear planes is reduced by one-third, but the maximum shear stress, which is the parameter determining whether dislocations will move, is not changed. Because the mobility of the dislocations appears to be a critical factor in the stress-corrosion mechanism for 7075-T6, specimens stressed uniaxially and biaxially should behave similarly in stress-corrosion tests. On the other hand, geometric considerations pertaining to the orientation of the specimen axis with respect to the nonoperative shear plane may result in differences.

The tests also include 347 stainless steel. Since the stress-corrosion mechanism in this material is less well understood, the behavior in a biaxial stress field was less predictable.

EXPERIMENTAL PROCEDURE

A tubular specimen having the design shown in Fig. 2 was selected for uniaxial and biaxial tests. Balanced biaxial tension (1:1) was obtained through a combination of axial loading and pressurization of the tubes.



*Dimensions of stainless-steel specimen are the same unless otherwise noted in parentheses

Figure 2. 7075-T6 Aluminum Stress-Corrosion Specimen

At the outset, a cross-type specimen was considered unsatisfactory, because the state of stress is not simple biaxial at the intersection of the arms. The use of bulge plates or pressurized spheres makes comparison with uniaxial stresses too difficult, because texture considerations would require that a very large number of differently oriented uniaxial specimens be tested. With pressurized and unpressurized tubes, however, the state of stress is uniform and the same orientation is stressed.

The 7075-T6 specimens were machined from a hand forging, 3-7/8 by 4 by 8 inches. Twenty-two specimens were taken from the short transverse direction and 18 from the long transverse direction. (Stress-corrosion results on aluminum alloys are known to be orientation-dependent.) A total of 42 stainless steel specimens were machined from 3/8-inch OD tubing having a 0.015-inch wall thickness.

Four aluminum specimens (specimens 19, 20, 21, and 22), with twice the wall thickness of the specimen shown in Fig. 2, were also tested to determine the effect of this parameter on stress-corrosion time-to-failure. Cross sections of the thin (0.008-inch) and thick (0.016-inch) walled tubes were polished and etched and photomicrographs taken. Similar metallography was performed on a stainless-steel specimen. The photomicrographs are shown in Fig. 3. Unlike the aluminum, the stainless steel does not show a strongly oriented grain structure.

The axial load was applied to the specimen in a U-type, stress-corrosion testing frame. A typical frame is shown in Fig. 4. Frames for the aluminum specimens were machined from 6061-T6 aluminum, and those for the 347 stainless steel specimens were machined from 321 stainless steel. The two spherically seated screws (bottom of testing frame in Fig. 4) were tightened successively in increments of $\sim$0.0003 inch, or less, until a strain corresponding to the desired stress level was reached. Elastic moduli of 10.4×10^6 and 28×10^6 psi were used for 7075-T6 and 347 stainless steel, respectively. The strain was measured by a 1-inch gage length extensometer and read on the strain recorder of a tensile testing machine. Despite the care exercised in applying the axial load, the introduction of a bending moment in the tubular specimens was inevitable, as indicated by measurements with paired strain gages positioned longitudinally on opposite sides of a stainless-steel specimen.

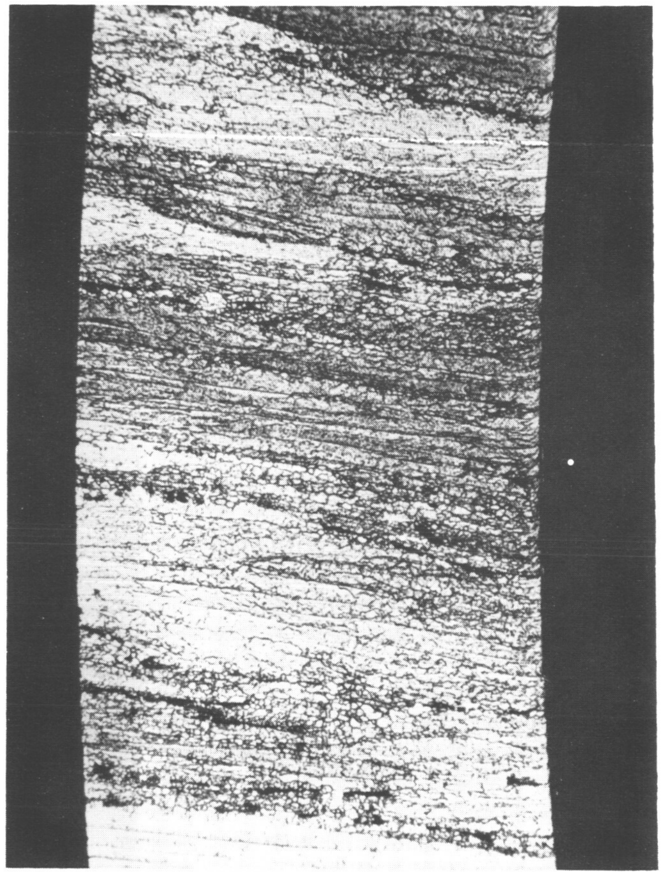


Figure 3a. Photomicrograph Showing Cross Section of Thin-Walled 7075-T6 Stress-Corrosion Specimen (200X)

Figure 3b. Photomicrograph Showing Cross Section of Thick-Walled 7075-T6 Stress-Corrosion Specimen (200X)

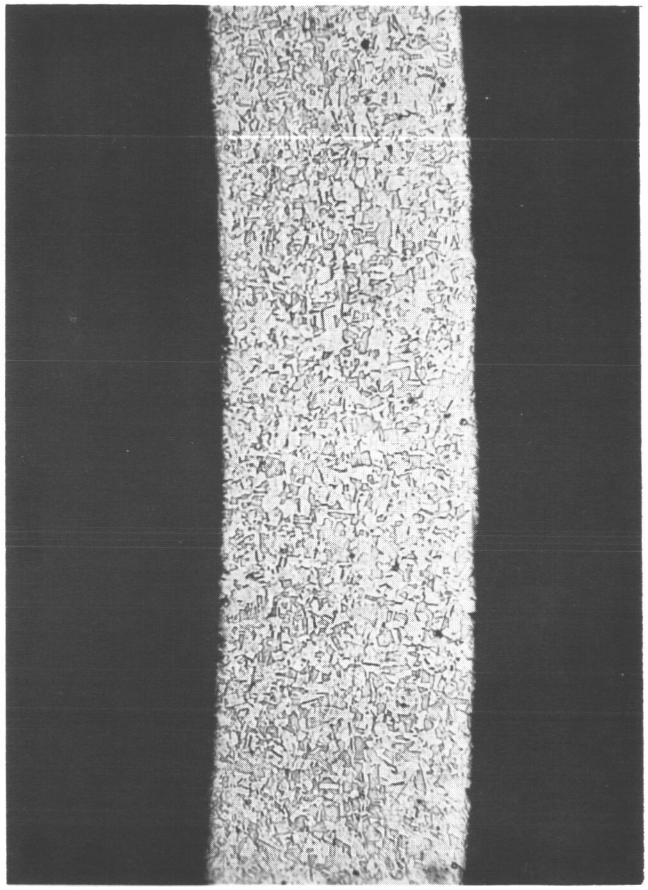


Figure 3c. Photomicrograph Showing Wall Cross Section of 347 Stainless-Steel Stress-Corrosion Specimen

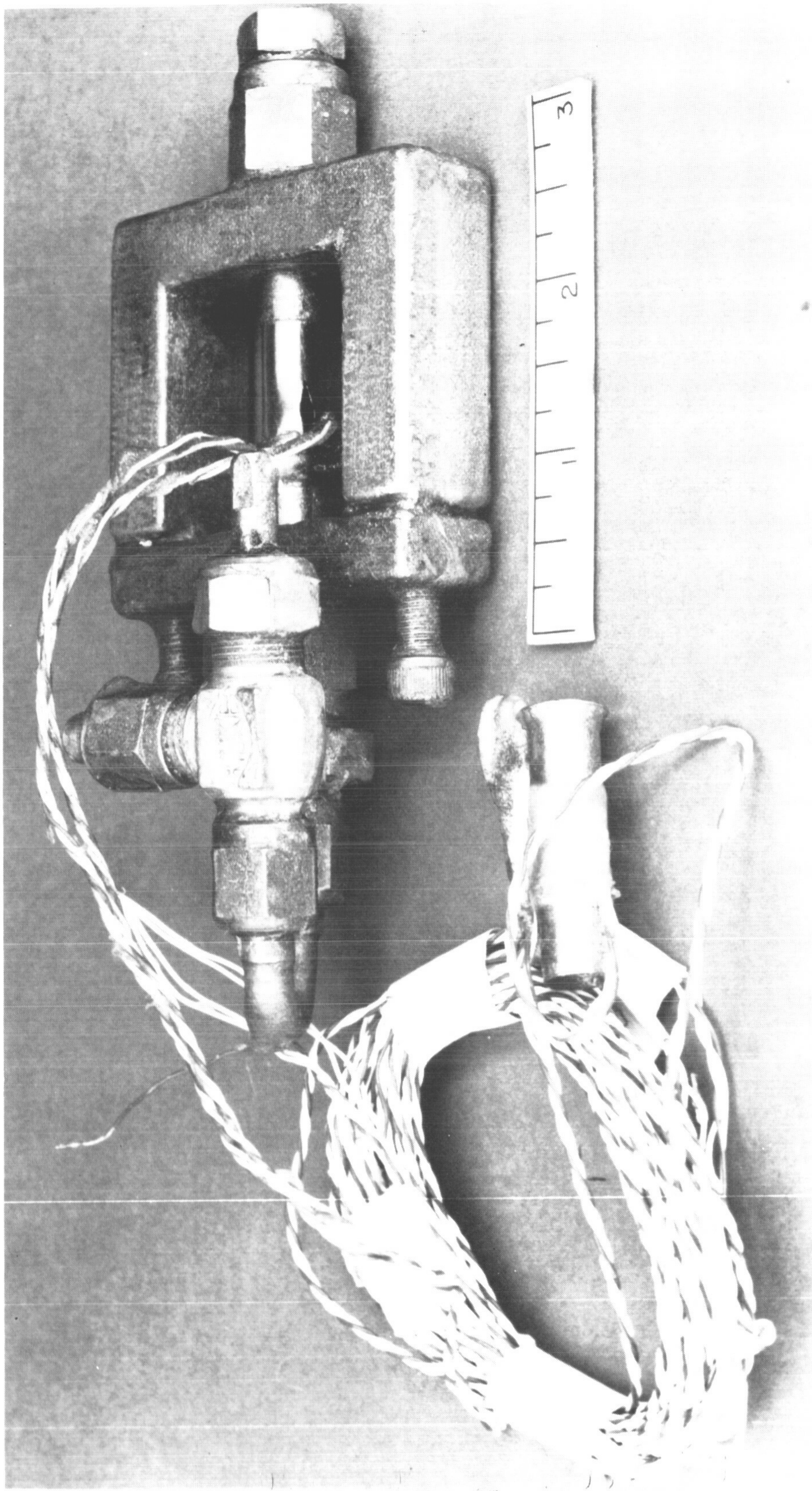


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Figure 4. Biaxially Loaded 347 Stainless-Steel Stress-Corrosion Specimen (Specimen No. 10)

Tests on the stainless-steel specimens were conducted at 50 and 65 percent of the average tensile yield strength, as determined in two tensile tests on as-received tubular stock. (The test on specimen 32 in Table 2, page 26, was conducted at 46 percent of yield, a stress which gave the same strain as did the 65 percent-of-yield stress in a biaxial specimen.) The short transverse aluminum alloy specimens were tested at 32.5 and 65 percent of yield, and the long transverse specimens at 65 and 80 percent of yield. Tensile properties were measured on two short transverse tubular specimens without reduced section. A summary of the tensile properties of the two materials is presented below:

	Specimen	Yield Strength (0.2 Percent Offset), psi	Tensile Strength, psi	Percent Elongation (1-Inch Gage Length)
347 Stainless Steel	1	63,800	95,200	45.0
	2	62,400	94,200	43.0
7075-T6	3	58,500	62,700	1.5
	4	54,400	63,000	4.0

The biaxial specimens, which were filled with a diffusion-pump oil (Convoil 120) before being loaded axially, were pressurized with helium. The pressure, P, was increased until the hoop stress, σ_h, in the reduced section was equal to the axial stress (Fig. 5). The relationship between P and σ_h is given by

$$P = \frac{\sigma_h t}{r}$$

where t is the reduced wall thickness and r is the radius extending to the mid-point of the reduced wall. The longitudinal stress, σ_l, which is one-half the hoop stress, accounts for one-half the overall axial stress, the

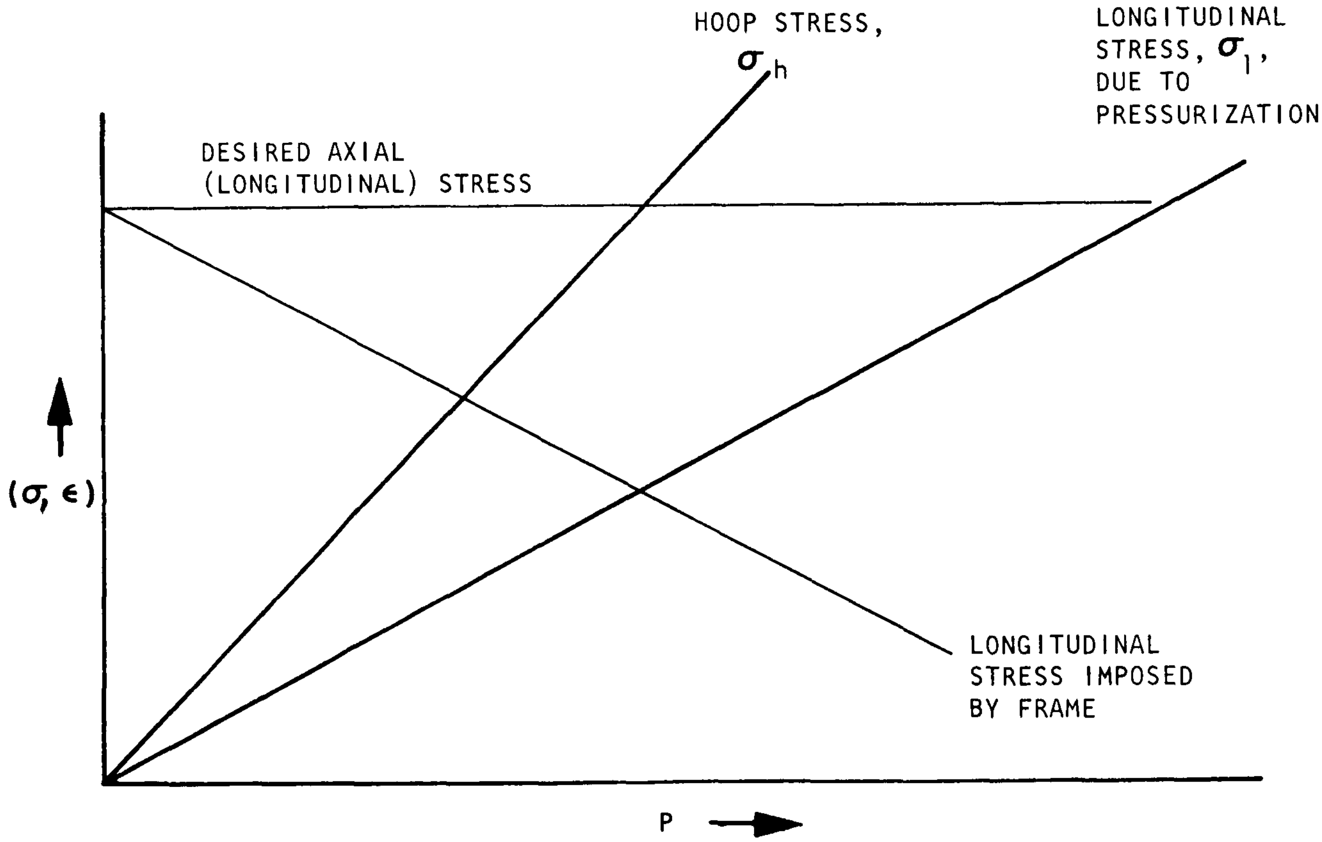

Figure 5. Plot of Stress and Strain (σ, ϵ) vs Pressure (P) Developed in Biaxially Loaded Stress-Corrosion Specimens

other half of the axial stress being imposed by the stressing frame. Half of the original stress imposed by the frame is relaxed during the pressurization, as indicated in Fig. 5. Strain gage measurements indicated that Poisson's effect could be neglected in calculating the pressure. These measurements confirmed that the stress was balanced biaxial.

A sample calculation is shown below. In this example, the pressure is calculated which is required to produce a hoop stress, σ_h, equal to 65 percent of the measured yield stress (56,500 psi) of 7075-T6 aluminum:

$$P = \sigma_h \frac{t}{r}$$

$$= 0.65 \ (56{,}500 \text{ lb/in.}^2) \ (0.008 \text{ inch}/0.177 \text{ inch})$$

$$= 1650 \text{ lb/in.}^2$$

The following table gives the pressure and strains calculated for the various stress levels.

	Strain, in./in.	Pressure, psi
347 Stainless Steel, percent TYS*		
65	0.00147	1850
50	0.00113	1425
46	0.00104	1310
7075-T6 Aluminum (0.008-inch wall), percent TYS*		
80	0.00434	2040
65	0.00351	1650
32.5	0.00176	825

*Tensile yield strength

Standard AN fittings were used on the flared ends of the stainless-steel specimens (Fig. 6). Since the ends of the aluminum specimens could not be flared without consequent cracking, recourse was made to "Swagelok" fittings, which do not require flaring (Fig. 7). For reasons of economy, brass valves were used on all of the biaxial specimens except those specially noted in Table 1. Commercial coatings, Turco Maskant 5145, and an epoxy, PT-401*, were applied to the aluminum and stainless-steel frames, respectively, to prevent galvanic effects between the frames and specimens. As will be pointed out in the Discussion of Results section, the PT-401 was unsuccessful in this respect.

The ability of the biaxial aluminum and stainless-steel test setups to maintain pressure during a test was investigated. Strain-gage (specimen 19) and mechanical-gage (specimen 15) checks on aluminum and checks performed with mechanical gages on stainless steel (specimen 21) inspired sufficient confidence to obviate a check of every biaxial test.

Aluminum specimens were subjected to alternate immersion tests. In this test, the specimen is automatically immersed for 10 minutes in a 3-1/2 percent NaCl solution and then dried in the air for 50 minutes. A typical immersion rack and NaCl tank are shown in Fig. 8.

The stainless-steel specimens were continuously immersed in a constant boiling (309 F) 42-percent aqueous $MgCl_2$ solution. Each specimen was exposed to a fresh solution of $MgCl_2$ contained in a modified Erlenmeyer flash with cold finger. As many as 12 flasks could be accommodated on the hot plate which was used, although usually six tests or less were conducted at one time (Fig. 9). Several cold fingers were fabricated with passages for thermometers and tubing.

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*Supplied by Turco Products, Inc., and Product Techniques, Inc., Los Angeles, California, respectively.

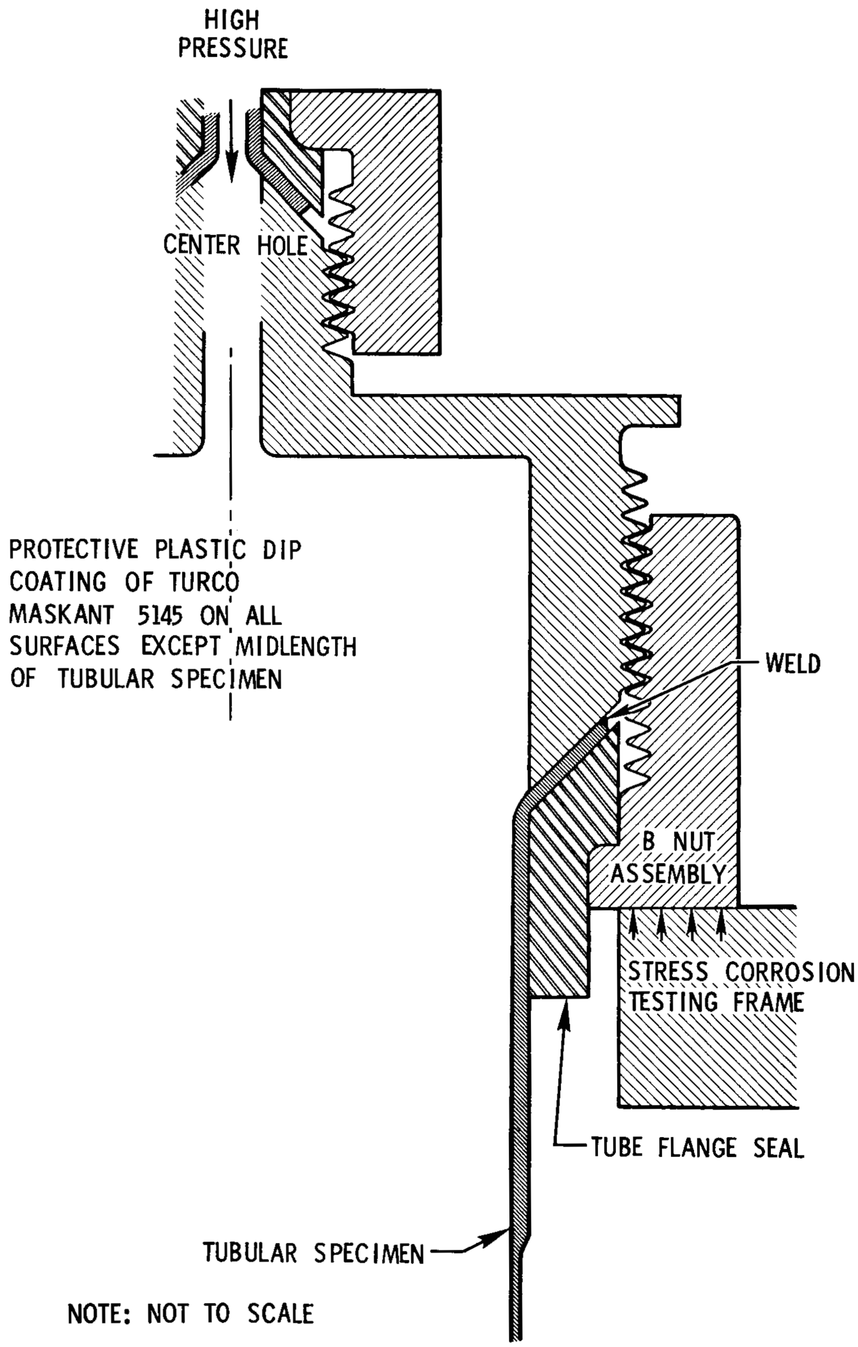
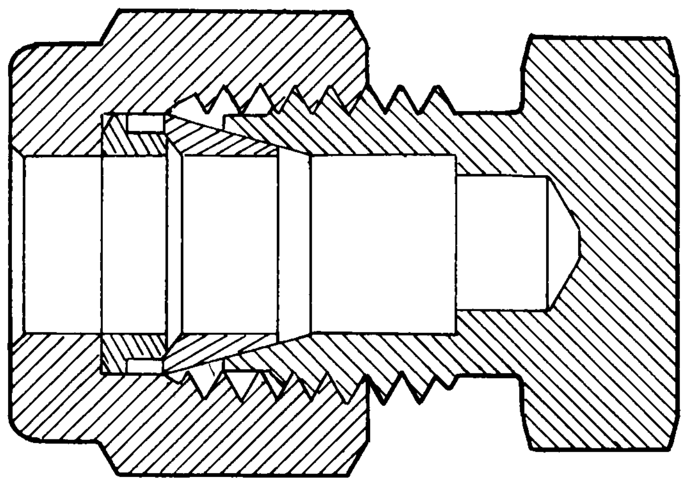
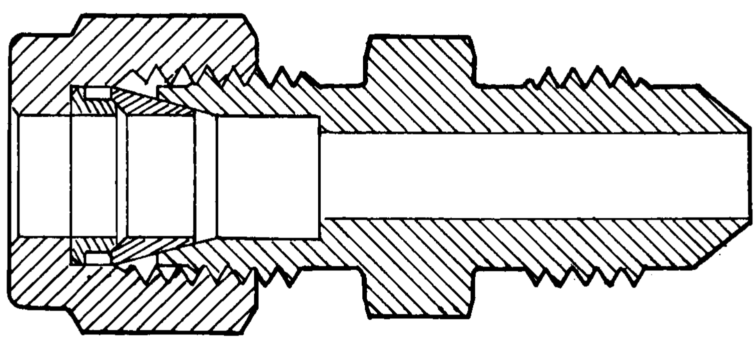


Figure 6. End of 347 Stainless-Steel Stress-Corrosion Specimen Showing High-Pressure Fittings



a. Swagelok Cap for Capping End of 7075-T6 Tube



b. Swagelok to AN Union

Figure 7. Swagelok Fittings Used on Biaxial 7075-T6 Aluminum Stress-Corrosion Specimen

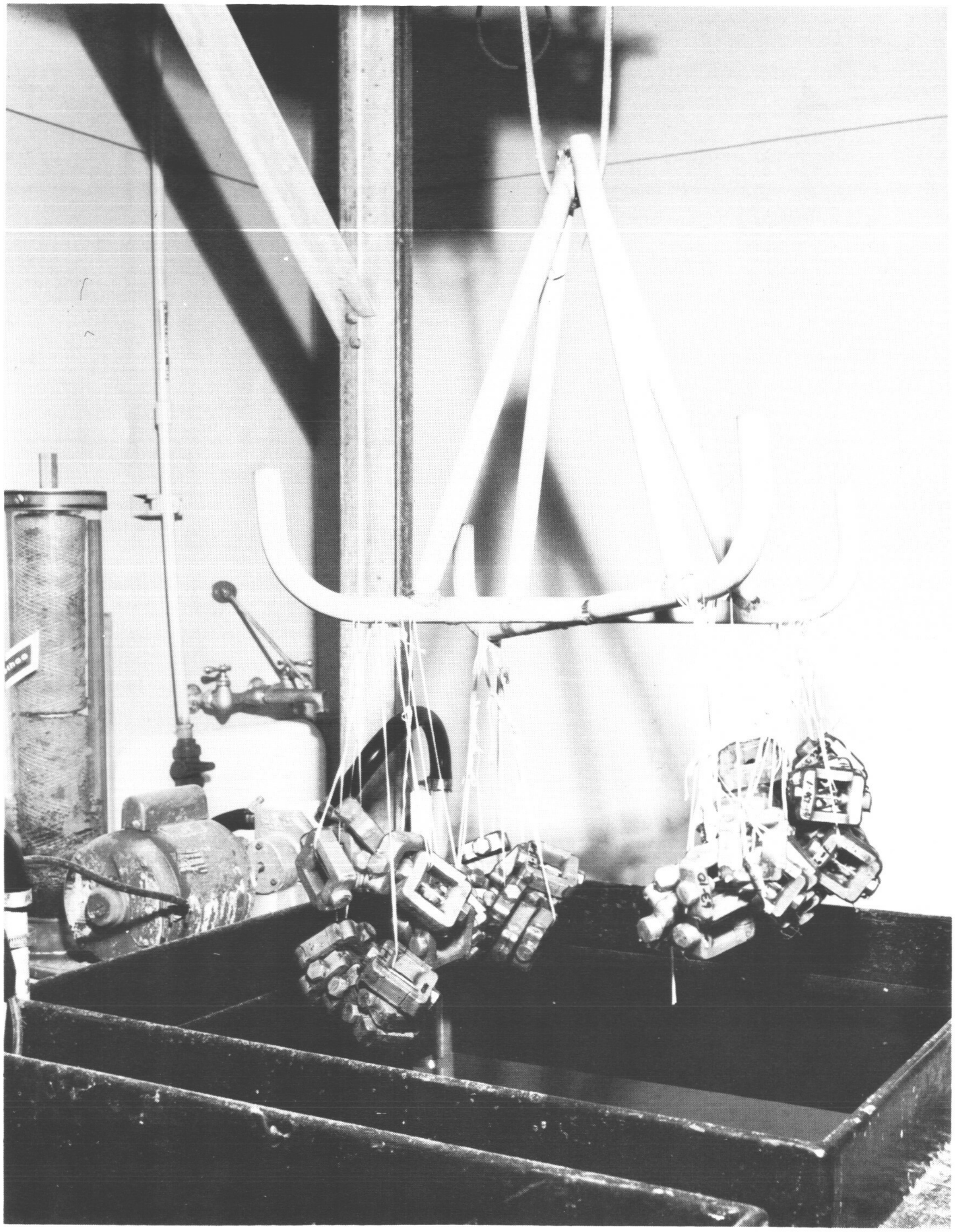


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Figure 8. Alternate-Immersion-Test Setup for 7075-T6 Specimens

5AG29-4/5/67-C1

Figure 9. Boiling $MgCl_2$ Stress-Corrosion Test on 347 Stainless Steel

The stress-corrosion tests were terminated either when the first crack was observed or when, in the case of the pressurized specimens, the first oil leak was noticed. To facilitate crack or leak detection, a red dye was added to the pressurizing oil inside the specimens indicated in Tables 2 and 3. The dye was ineffective after times greater than ~ 2 days at 309 F.

The detailed procedures used to prepare specimens for testing are outlined in Table 1.

TABLE 1

PROCEDURES USED TO PREPARE UNIAXIAL AND BIAXIAL ALUMINUM AND STAINLESS-STEEL STRESS-CORROSION SPECIMENS FOR TESTING

7075-T6 Aluminum	
Uniaxial	Biaxial
1. Specimen cleaned ultrasonically in alcohol. Stress-corrosion frame cleaned with acetone.	1-4. Same as Uniaxial 1 through 4
2. Specimen assembled in stress-corrosion frame with Swagelok fittings	5. Specimen pressurized
3. Specimen filled with oil-dye mixture, cleaned with acetone	6-9. Same as Uniaxial 5 through 9
4. Specimen loaded uniaxially in tension	
5. Specimen cleaned with acetone	
6. Gage section covered with masking tape	
7. Three coats of Turco Maskant 5145 applied to frame. Each coat degassed in vacuum (20 to 25 inches Hg). Masking tape removed before each coat is dry, and re-applied before next coat	
8. Shrinkage holes in coating repaired with paraffin	
9. Gage section cleaned with toluene	

TABLE 1

(Concluded)

347 Stainless Steel	
Uniaxial	Biaxial
1. Specimen and frame cleaned with acetone	1-8. Same as Uniaxial 1 through 8 up to and including first coat of PT-401
2. Specimen flared and assembled with standard AN fittings. One of two B-nuts tightened.	9. Specimen pressurized while in boiling $MgCl_2$ solution (309 F)
3. Specimen filled with oil-dye mixture	10. Second and third coats of PT-401 applied to frame and degassed
4. Second B-nut tightened	11. Same as Uniaxial
5. Specimen loaded uniaxially in tension, cleaned with acetone	
6. Gage length of specimen covered with masking tape	
7. Stress-corrosion frame sprayed with epoxy PT-401 primer	
8. Two (specimens 1 through 18) or three coats (specimens 19 through 42) of PT-401 brushed onto frame and degassed in vacuum (20 to 25 inches Hg)	
9. Masking tape removed from specimen	

RESULTS

The results of 42 tests on 347 stainless steel and 40 tests on 7075-T6 aluminum are contained in Tables 2 and 3. The times-to-failure (t_f) in the last column of the table are reported in hours and minutes unless otherwise noted. Uncertainties in t_f are actually the elapsed times between the next-to-last and the final observations. In certain cases of very low t_f where only one observation was made, or where the initial crack is believed to have escaped prompt detection, the time is preceded by the symbol < ("less than"). The specimens were unattended during the night, which accounts for the largest uncertainty.

347 STAINLESS STEEL

The uniaxial specimens stressed at 65 percent of yield failed in less than 1 day, most of the failure times varying between 3 and 15 hours. Rather large stress-corrosion cracks were detected in the threaded cross-bars of frames 3 and 5, and barely detectable cracks were found in three more cross-bars after the frames had been dismantled and their identification lost. Thus, three uniaxial specimens (not including 3 and 5) might have been stressed at somewhat less than 65 percent of yield. The cracked cross-bars were replaced by thicker pieces, and as a further precaution, the freshly applied coats of epoxy were degassed in vacuo so that holes and crevices would be filled more efficiently and seepage of the solution under the coating prevented. No further cracking of the frames was thereupon encounterd. Specimens 7 and 15 cracked outside the gage section.

The first 10 biaxial specimens to be tested at 65 percent of yield (10 through 13, 16 through 21) were fitted with brass valves. Tests on three

TABLE 2

STRESS—CORROSION TEST RESULTS FOR 347 STAINLESS STEEL

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
1	Uniaxial (U)	65		15-30 ±5-40
2	U	65		14-48 ±7-43
3	U	65	Cracking of stress-corrosion testing frame	-
4	U	65		<24-45
5	U	65	Cracking of stress-corrosion testing frame	-
6	U	65	Fine crack in shoulder area believed to have escaped prompt detection	<54-30
7	U	65	Crack outside reduced section	-
8	U	65		14-48 ±7-43
9	U	65		<7-50
14	U	65	Dye	4-19 ±0-19
15	U	65	Crack outside reduced section	-
39	U	65	Stainless steel valve. Dye.	3-33 ±0-18
40	U	65	Stainless steel valve. Dye.	3-10 ±0-35

TABLE 2

(Continued)

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
10	Biaxial (B)	65	Strain gage on specimen to monitor pressure changes	4-6 ±0-30
11	B	65	Dye	DNF 7 days
12	B	65	Dye	DNF 7 days
13	B	65	Dye	DNF 7 days
16	B	65	Crack in fitting	27 days
17	B	65		397-28 ±32-8
18	B	65	Crack in fitting	19 days
19	B	65		DNF 28 days
20	B	65	Strain gage on frame to monitor pressure changes	< 1-10
21	B	65	Mechanical gage used to monitor pressure changes	< 1-10
33	B	65	Stainless-steel valve--nonstainless handle. Dye.	DNF 5 days
34	B	65	Broke during pressurization	-
35	B	65	Stainless-steel valve--nonstainless handle. Dye.	DNF 5 days
36	B	65	Stainless-steel valve	1-3 ±0-23
37	B	65	Stainless-steel valve	0-55 ±0-15
38	B	65	Stainless-steel valve	< 0-45

TABLE 2
(Concluded)

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
22	U	50	Dye	2-35 ±0-35
23	U	50	Dye	2-35 ±0-35
24	U	50	Dye	3-18 ±0-8
25	U	50	Dye	76-51 ±2-24
26	U	50	Dye	7-23 ±0-32
27	U	50	Dye	3-10 ±0-15
28	U	50	Dye	8-25 ±0-30
29	U	50	Dye	3-10 ±0-15
30	U	50	Dye	3-10 ±0-15
32	U	46	Hardware same as on biaxial specimen including brass valve. Dye.	DNF 33 days
31	B	50		DNF 33 days
41	B	50	Stainless steel valve. Dye.	$<$0-48
42	B	50	Stainless steel valve. Dye.	2-50 ±0-15

TABLE 3

STRESS-CORROSION TEST RESULTS FOR 7075-T6

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
Short Transverse Orientation				
1	Uniaxial (U)	65		14-50 ±8-4
2	U	65		14-50 ±8-4
3	U	65		14-50 ±8-4
4	U	65		14-50 ±8-4
5	U	65		14-50 ±8-4
6	Biaxial (B)	65		26-33 ±2-40
7	B	65		14-50 ±8-4
8	B	65		14-50 ±8-4
9	B	65		26-33 ±2-40
10	B	65		50-8 ±2-15
11	U	32.5		13-2 ±2-41
12	U	32.5		25-14 ±9-31
13	U	32.5		25-14 ±9-31
14	U	32.5		25-14 ±9-31
21	U	32.5	Thick (0.016-inch) walled tube. Dye.	135-28 ±8-23
22	U	32.5	Thick (0.016-inch) walled tube. Dye.	DNF 18 days

TABLE 3

(Continued)

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
15	B	32.5	Mechanical gage used to monitor pressure changes	38-5 ±12-29
16	B	32.5	Dye	40-54 ±12-3
17	B	32.5	Dye	62-56 ±10-0
18	B	32.5	Dye	40-54 ±12-3
19	B	32.5	Thick (0.016-inch) walled tube. Strain gage on specimen to monitor pressure changes	544-8 ±13-2
20	B	32.5	Thick (0.016-inch) walled tube. Dye.	107-23 ±11-58
Long Transverse Orientation				
23	U	80	Dye	63-20 ±8-28
24	U	80	Dye	63-20 ±8-28
25	U	80	Dye	48-25 ±0-23
26	U	80	Dye	63-20 ±8-28
27	U	80	Dye	423-22 ±12-0
28	B	80	Dye	35-50 ±12-13
29	B	80	Dye	48-37 ±0-35
30	B	80	Dye	63-20 ±8-28
31	B	80	Dye	63-20 ±8-28

TABLE 3

(Concluded)

Specimen No.	State of Stress	Stress Level, percent of yield strength	Remarks	t_f, hours and minutes
32	B	80	Dye	63-20 ±8-28
33	U	65	Dye	88-2 ±9-52
34	U	65	Dye	75-0 ±3-11
35	U	65	Dye	100-10 ±2-16
36	U	65	Dye	100-10 ±2-16
37	B	65	Dye	41-49 ±10-51
38	B	65	Dye	75-0 ±3-11
39	B	65	Dye	112-8 ±9-43
40	B	65	Dye	100-10 ±2-16

of these specimens (11 through 13) were terminated after 7 days with no failure, and on a fourth specimen (19) after 28 days without failure. Two additional tests (16 and 18) were concluded after 19 and 27 days, respectively, when the fittings started to leak. A seventh specimen (17) failed on the eighteenth day. The remaining three tests (10, 20, and 21), in which strain gages were affixed either to the specimen (10) or to the frame (20), or in which extra hardware (mechanical pressure gage, etc.) was connected to the specimen (21), resulted in rapid (4 hours or less) failures.

Specimens 33 and 35, which had stainless-steel valves with nonstainless-steel handles, also showed signs of surviving the $MgCl_2$ solution for many days when the tests were terminated on the fifth day. When the nonstainless-steel handle was removed from the valve, as in tests 36 through 38, the specimens failed in 1 hour or less.

Similar results were obtained with specimens at the 50 percent-of-yield-stress level. Those uniaxial specimens having all-stainless steel constructions failed in about 9 hours or less; the lone exception was specimen 25. Specimen 32, which was fitted with a brass valve to simulate the original biaxial test setup, did not fail in 33 days of testing. This specimen was tested at 46 percent of yield instead of 50 percent,so it would be strained the same amount as a biaxial specimen stressed at 65 percent of yield.

The biaxial specimens stressed at 50 percent of yield failed in 3 hours or less (specimens 41 and 42) or did not fail in 33 days (specimen 31), depending on whether the setup was all-stainless steel or whether it contained a brass valve, respectively.

Five of the 42 stainless-steel specimens broke into two parts. These included two uniaxial and two biaxial specimens stressed at 65 percent of yield and one uniaxial specimen stressed at 50 percent of yield. Multiple cracks, none completely traversing the specimen, formed in the remaining 37 specimens.

7075-T6 ALUMINUM

Short Transverse Orientation

The uniaxial 7075-T6 aluminum alloy specimens tested at the higher (65 percent of yield) stress level all failed in about 15 hours, whereas biaxial specimens under the same stress tended to last slightly longer (from 15 to 51 hours). The same tendency was observed with the thin (0.008-inch) walled specimens stressed at 32.5 percent of yield; the uniaxial specimens had a t_f between 13 and 25 hours, while the biaxial specimens survived between 38 and 63 hours of testing. Four thick (0.016-inch) walled specimens tested at the lower stress level gave erratic results. One of the uniaxial specimens failed in 135 hours while the other did not fail in 18 days, and the biaxial specimens failed in 107 and 544 hours, respectively.

Long Transverse Orientation

Uniaxial and biaxial aluminum alloy specimens tended to fail in about the same time, at both stress levels. The times-to-failure at the higher stress level (the state of stress being held constant) were generally shorter than times at the lower stress level, although there was some overlap in the case of the biaxial specimens. The long transverse specimens tended to have longer lifetimes than the short transverse specimens at 65 percent of yield; however, there was some overlap for the biaxial specimens.

Most of the aluminum alloy specimens (70 percent of the short transverse and 80 percent of the long transverse) tested at the higher stress levels broke into two parts. Multiple cracking occurred in all the short transverse specimens stressed at 32.5 percent of yield and in all the long transverse specimens stressed at 65 percent of yield (Fig. 10).

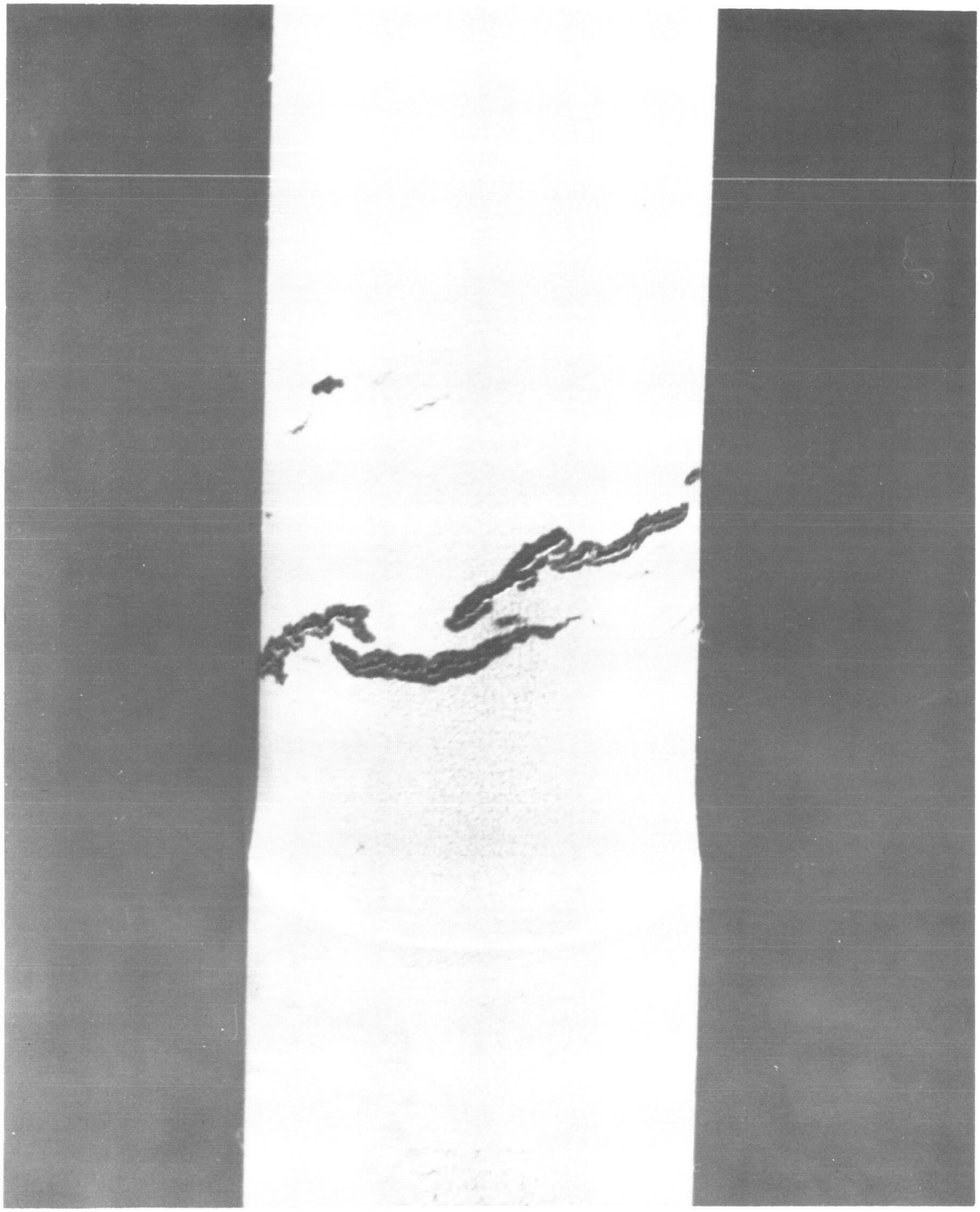

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Figure 10. Multiple Cracking Observed in Short Transverse 7075-T6 Stress-Corrosion Specimen Biaxially Loaded to 65 Percent of Yield. (Cracks Revealed With Zyglo Penetrant ZL-H)

DISCUSSION OF RESULTS

347 STAINLESS STEEL

In contrast to uniaxially stressed specimens, which tended to fail the boiling $MgCl_2$ test in 1/2 day or less, the biaxial specimens either failed early (4 hours or less) or did not fail after days of testing. Those specimens with all-stainless steel connections failed early as did the three specimens connected with strain gages or extra hardware (mechanical pressure gage, etc.). In fact, stainless-steel valves were not used on biaxial specimens until it was suspected from the uniaxial test on specimen 32 that the epoxy coating was electrically conducting and that the brass valves, therefore, could be cathodically protecting the stainless-steel specimens. The test on specimen 32, which was fitted with a brass valve and other hardware comprising the original biaxial setup, lasted for 33 days without failure of the specimen. This test was unlike all of the other uniaxial tests, which resulted in rapid failure. Precision electrical resistance measurements confirmed that within minutes after initial exposure to the boiling $MgCl_2$ solution, the PT-401 epoxy coating was losing most of its resistance and that the loss was progressive with time. There was a discoloration of the solution which indicated dissolution of the coating, but this occurred very gradually, and was barely noticeable during the first few days of testing when the uniaxial specimens generally failed and the biaxial specimens did not. Thus, there was no obvious reason to ascribe the significant difference in lifetime of uniaxial and biaxial specimens to galvanic effects that suddenly arose from a nonprotective coating.

The tests carried out subsequent to the electrical measurements provided additional evidence that the biaxially stressed specimens were not inherently superior to the uniaxial specimens. It was possible to run only a limited number of tests during the remainder of the program (specimens 36 through 42), so an unequivocal comparison of the two stress states could not be drawn. The associated hardware for specimens 36 through 42 was identical. Any differences in t_f between 36 through 38 (biaxial, 65 percent of yield) and 39 and 40 (uniaxial, 65 percent of yield) could only be attributed to a difference in stress state. Also, any differences between 36 through 38 (biaxial, 65 percent of yield) and 41 and 42 (biaxial, 50 percent of yield) had to be due to the difference in stress level. As shown in Fig. 11, the results suggest that biaxial loading reduces the time-to-failure. The mean t_f for biaxial specimens 36 through 38 is 47 minutes, while the mean t_f for uniaxial specimens 39 and 40 is 202 minutes. The results also suggest the expected difference in t_f for specimens loaded at 50 and 65 percent of yield. From the standpoint of statistical significance,additional tests are required to verify these results.

The early failures of biaxial specimens 10, 20, and 21 (Table 2), which were monitored for pressure changes with strain gages or a mechanical gage, can be explained as follows. The brass valves in the three setups could not provide cathodic protection. In the setup including the mechanical gage, the valve was out of the solution, and thus was not part of a closed electrical circuit. In the setups containing strain gages, it appears probable that the constantan (55Cu-45Ni) gage was interfering in some unknown way with the anode-cathode relationship between valve and specimen. These gages were not only coated but were also backed with an epoxy. The vulnerability of the epoxy on stressing frames to boiling $MgCl_2$ strongly suggests that the epoxy on the gages also became conducting.

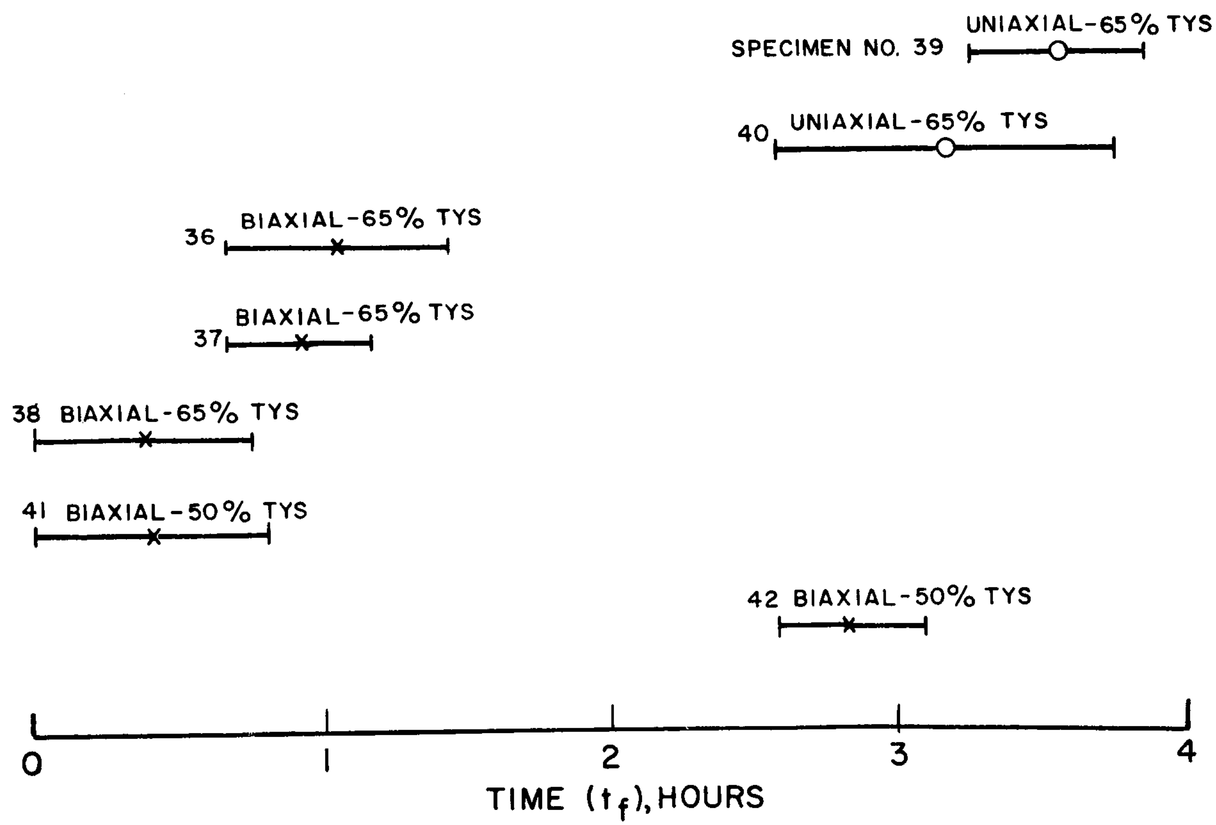

Figure 11. Stress-Corrosion Results for Uniaxial and Biaxial 347 Stainless-Steel Specimens Having Identical Associated Hardware

7075-T6 ALUMINUM

A slight tendency was evidenced for biaxial loading to prolong the stress-corrosion lifetime of short transverse 7075-T6 specimens. However, no difference was observed between uniaxial and biaxial specimens tested in the long transverse orientation. The difference in the short-transverse case is in the opposite direction to that suggested by the limited results for 347 stainless steel. The model that has been developed at Rocketdyne for stress-corrosion cracking of aluminum (Ref. 5) predicts similar $t_{f's}$ in the presence of uniaxial or balanced biaxial stresses.

Results for the two different orientations were consistent, insofar as the effect of stress level on t_f was concerned. Lowering the stress level from 65 to 32.5 percent of yield in the case of the short transverse specimens, and from 80 to 65 percent of yield in the case of the long transverse specimens, resulted in a greater average t_f, as expected.

The reason for the erratic results obtained with the thick (0.016-inch) walled specimens (19 through 22) is not clear. These specimens would be expected to have a longer lifetime than the thin-walled specimens, which in fact was observed. However, t_f varied between 6 and >18 days for the uniaxial specimens and between 4 and 23 days for the biaxial specimens, making comparison with results for thin-walled specimens impossible.

Effect of Bending Moment

As mentioned in the Experimental Procedures section, a bending moment was introduced in the specimens during axial loading. The magnitude of this moment undoubtedly varied from specimen to specimen and is probably the cause of most of the scatter in the data. The magnitude of the stress change caused by the bending was not significantly affected by pressurizing the tube for the biaxial tests. Thus, the bending should not have been the cause of any difference in behavior between the uniaxial and biaxial groups of specimens.

CONCLUSIONS

The following conclusions are drawn from this investigation:

1. Balanced biaxial tension differs little from uniaxial tension in its effect on the stress-corrosion susceptibility of 7075-T6 aluminum alloy.
2. On the basis of limited data, balanced biaxial tension as opposed to uniaxial tension appears to increase the susceptibility of 347 stainless steel to stress-corrosion cracking.

REFERENCES

1. Jacobs, A. J.: "The Role of Dislocations in the Stress-Corrosion Cracking of 7075 Aluminum Alloy," ASM Trans Quart, 58, 579 (1965).
2. Jacobs, A. J.: "The Effect of Explosive Deformation on the Stress-Corrosion and Mechanical Properties of 7075 Aluminum Alloy," Paper presented at the AIAA Seventh Structures and Materials Conference, Cocoa Beach, Florida (18-20 April 1966).
3. Jacobs, A. J.: "How Dislocations Affect Stress-Corrosion Cracking in Aluminum Alloys," Metal Progress, 89, 80 (1966).
4. Jacobs, A. J.: "Stress-Corrosion Cracking of Aluminum," Nature, 211, 403 (1966).
5. Jacobs, A. J.: "A New Model for Stress-Corrosion Cracking in the 7075 Aluminum Alloy," Paper presented at the 1966 National Metal Congress, Metal Science Forum on Stress Corrosion, Chicago, Illinois, 1 November 1966.

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13. ABSTRACT

The experimental program was carried out to determine the effect of a biaxial (1:1) stress state on the stress-corrosion resistance of 7075-T6 aluminum and 347 stainless steel. Tubular specimens of these alloys were loaded in simple tension or were loaded in tension and pressurized to obtain the biaxial stress state. A total of 40 aluminum specimens, 20 short transverse and 20 long transverse, were subjected to alternate-immersion tests in a 3-1/2 percent NaCl solution at room temperature. The short transverse specimens were tested at 65 and 32.5 percent of yield strength, and the long transverse specimens at 80 and 65 percent of yield. Forty-two stainless-steel specimens were continuously immersed in a constant boiling (309 F) aqueous solution of $MgCl_2$. These were investigated at 50 and 65 percent of their yield strength. Balanced biaxial loading compared with uniaxial loading is as follows in its effect on stress-corrosion life. The short transverse 7075-T6 specimens tended to survive somewhat longer under biaxial loading; however, there was no discernible effect in the case of long transverse specimens. A tendency was observed for the lifetime of 347 stainless steel specimens to be shortened under the application of biaxial stress. A number of the stainless-steel tests were invalidated because the epoxy coating on the stressing frames was permeable to the $MgCl_2$ solution.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Stress-Corrosion Cracking						
Biaxial Stress						
7075-T6 Aluminum						
347 Stainless Steel						

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